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SECONDARY AIRFLOW AND SEDIMENT TRANSPORT IN THE LEE OF A REVERSING DUNE

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ABSTRACT

Lee-side windspeed and sediment transport were measured over a small (1·2 m) transverse ridge in the Silver Peak dunefield, west-central Nevada, USA, using an intensive array of 25 cup anemometers and seven total flux traps. During crest-transverse and transporting flow conditions ($u_{0\cdot3\mathrm{crest}} \approx 8\cdot4$ m s^{-1}), windspeed near the surface of the lee slope averaged half (48 per cent) that of crest speeds. Dimensionless speeds in the separation zone ranged from 0·2 to 0·8 that of the outer flow (u_{12}). Along the boundary of the separation cell, windspeed increased by 10 per cent of the crest speed before separation. Equilibrium of upper and lower wake regions was not observed by the documented eight dune heights, suggesting that wake recovery may not occur over closely spaced dunes.

Sediment transport measured directly on both the lee slope and interdune surfaces averaged approximately 15 per cent of crest inputs. This suggests that a significant amount (*c.* 70–95 per cent) of sediment transported over the crest moved as fallout. For this data set, flux was approximately proportional to the cube of the near-surface windspeed ($u_{0\cdot3}$) and in general there was an order of magnitude difference between flux measured at the crest and that measured within the separation zone. Transport direction in the separation zone was acutely oblique to the incident direction owing to secondary flow deflection. Beyond the interdune, transport direction progressed from oblique to crest-transverse. This indicates that an appreciable amount of sediment may move laterally along the lee slope and interdune corridor under crest-transverse flows. Regarding the grain size and sorting properties of transported sediment, there was no significant difference in mean grain size over the dune, although in general particles were finer and more poorly sorted in the lee.
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KEY WORDS: dune; lee; airflow; sediment transport

INTRODUCTION

Sedimentary bedforms project into the airstream altering primary near-surface boundary layer flows. Resultant flow patterns over the bedform are secondary in that their vertical velocity distributions, or profiles, deviate from the expected log-linear form (i.e. the Law of the Wall). Secondary flows generate spatial differences in the distribution of fluid velocity, pressure and shearing stress over the form. In response, variations in sediment flux occur resulting in regions of localized transport and deposition. As such, sedimentary bedforms reflect the complex interactions and continuous feedbacks between flow, form and sediment transport.

Although secondary flow patterns such as lee flow separation and reversal are often referred to in the aeolian literature, the physical properties and sedimentological implications of such patterns remain poorly understood. This is not to say that research into dune lee airflow is lacking. Rather, considerable work has been done on describing lee flow and sediment transport, particularly for longitudinal dunes (e.g. Bagnold, 1953; Folk, 1970, 1976; Wilson, 1972; Tsoar, 1978, 1982, 1983; Tsoar *et al.*, 1985; Livingstone, 1986; Tseo, 1993). However, research on lee flow for transverse dunes is less extensive (e.g. Sweet and Kocurek, 1990; Sweet, 1992; Frank, 1994; Frank and Kocurek, 1996a) and is particularly sparse regarding implications for sediment transport.

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Of the numerous studies investigating sediment transport over aeolian dunes, most have focused mainly on the windward (stoss) slope (e.g. Lancaster, 1985; Burkinshaw and Rust, 1993; Lancaster *et al.*, 1996; Wiggs *et al.*, 1996; McKenna Neuman *et al.*, 1997). Studies of lee-side sediment transport are fewer and have concentrated most on deposition from fallout (e.g. Hunter, 1985; Anderson, 1988; Hand and Bartberger, 1988; Kocurek *et al.*, 1992). With the exception of Tsoar's work on longitudinal dunes (reviewed in Tsoar, 1989), very few studies have explored the linkage between secondary flow and surface transport in the lee, particularly for transverse dunes.

It is recognized in both the aeolian and fluvial literature that lee-side flow patterns and resultant sediment transport are influenced by, and have important implications for, transverse dune shape, size, spacing and alignment. For instance, dune spacing influences the nature of lee flow by way of stagnation effects (e.g. Howard *et al.*, 1978; Lancaster, 1985; Wiggs *et al.*, 1996), boundary layer transition signatures (e.g. Sherman and Bauer, 1993), flow sheltering and skimming effects (e.g. Lee and Soliman, 1977; Mulhearn and Finnigan, 1978) and location of flow reattachment (e.g. Engel, 1981; Nelson and Smith, 1989). More specifically, Frank and Kocurek (1996a) suggest that by eight dune heights downwind 'flow recovery' occurs whereby upper and lower wake regions equilibrate to form a single profile that extends up from a developing inner boundary layer. It is possible though that this observation may not hold in closely spaced bedform configurations because separation zones (and related secondary flow patterns) may extend onto, and may be influenced by, the stoss slope of the next dune. This, in turn, may result in flow reattachment occuring closer to the point of separation within multiple dune settings. This has important implications for inner boundary layer development and thus sediment transport over closely spaced dunes that may be distinctly different from relatively isolated dunes of similar shape and size. Furthermore, potential longitudinal (along-dune) components of lee-side flow and sediment transport have been overlooked in most existing two-dimensional approaches to modelling flow over dunes. These patterns have important implications for transverse dune spacing and may also introduce a lateral component to dune sediment budgets.

This paper documents the spatial variability in windspeed, sediment flux and particle size and sorting characteristics in the lee of a small (1·2 m high) reversing dune. The purpose is to characterize lee-side flow properties in a closely spaced dune setting and relate these to directly measured surface flux. From this, implications for the mode, direction and relative amount of lee-side sediment transport under crest-transverse flow conditions are discussed.

STUDY SITE

Windspeed profiles and surface sediment transport were measured in the lee of a small reversing dune in the northwestern part of the Silver Peak dunefield in the Clayton Valley, west-central Nevada, USA (Figure 1). The study site was located along a 15 m straight-crested portion of dune within a successive grouping of similarly sized ($h \approx$ 1–2 m), unvegetated, transverse ridges. These dunes are composed of loose, dry, fine sands ($D \approx 150$ μm) and are oriented transverse (75° or approximately E–W) to relatively consistent north winds. However, reversing winds do occur on occasion. During the period of study (May 1997) flow was approximately transverse to the crest and the dune had a sharp crestline with a distinct, southward-facing lee slope. Dune height was 1·2 m and stoss slope and lee slope lengths were 9·4 and 3·5 m respectively (Figure 2). Lee slope angle averaged 18° although a small slip face was evident at times on the upper portion of the slope. Dune aspect ratio was 0·13 indicating a relatively low-relief bedform. This dune is similar in profile to one investigated by Frank and Kocurek (1996a, p.454) on Padre Island, Texas.

METHODS

A sampling transect was established 11 m leeward and perpendicular to the crest of the study dune (Figure 2). Twenty-five R.M. Young Wind Sentry cup anemometers were deployed along six vertical instrumentation profiles. Instruments were extended on 1·25 m booms from one of four aluminium masts and were connected to dataloggers via cable. Near-surface anemometers were placed at 0·3 m to measure transporting windspeeds ($u_{0 \cdot 3}$). The dashed horizontal lines in Figure 2 indicate instruments at the same elevation.

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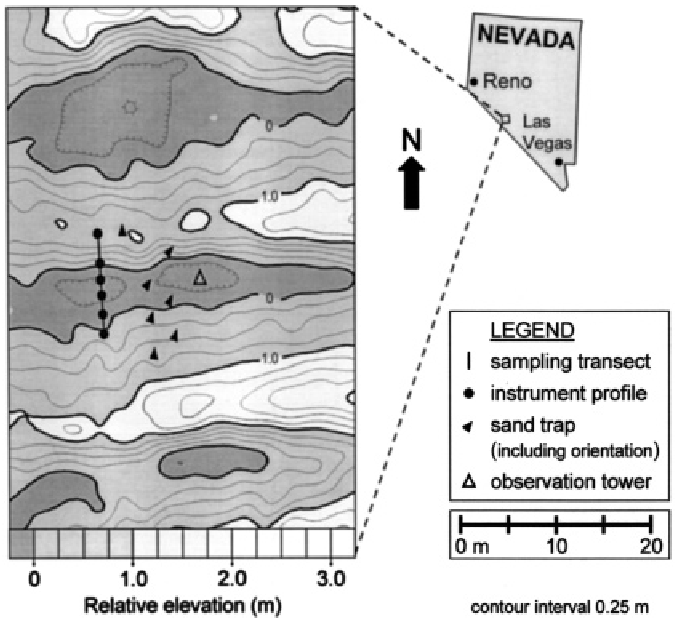

Figure 1. Study site location and dune topography. Included are instrument profile and sediment trap locations

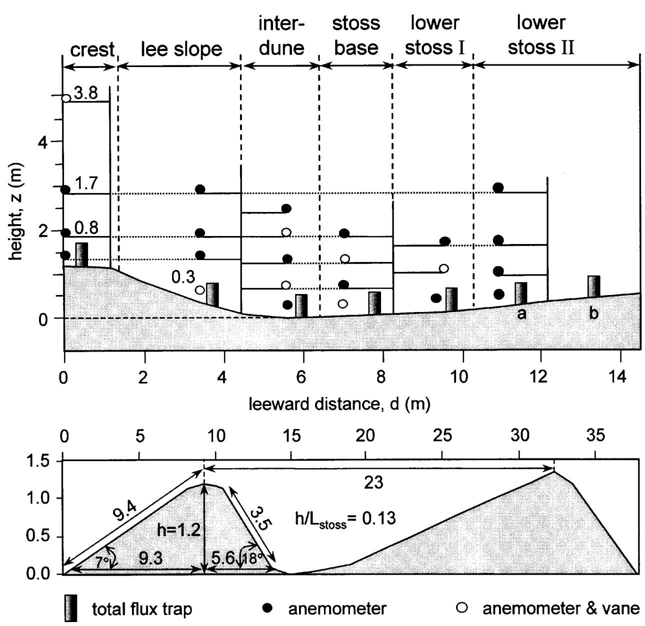

Figure 2. Instrument sampling transect design including instrument locations, flow regions and dune profile geometry. Dotted horizontal lines represent instruments at the same relative elevation. Note the vertical exaggeration on the dune profile diagram

Table I. Summary of data for flux runs 2, 4 and 8

Location	Run 2			Run 4			Run 8		
	$u_{0\cdot3}$ (m s^{-1})	q (kg m^{-1} s^{-1})	azimuth (degrees)	$u_{0\cdot3}$ (m s^{-1})	q (kg m^{-1} s^{-1})	azimuth (degrees)	$u_{0\cdot3}$ (m s^{-1})	q (kg m^{-1} s^{-1})	azimuth (degrees)
Crest	8·66	0·0331	5	8·74	0·0159	0	7·86	0·0192	10
Lee slope	3·56	0·0022	80	4·26	0·0047	75	4·09	0·0007	85
Interdune	2·92	0·0043	45	4·54	0·0048	65	2·90	0·0007	50
Stoss base	3·31	0·0017	10	4·89	0·0017	15	3·99	0·0011	10
Lower stoss I	4·36	0·0057	20	5·80	0·0065	30	4·71	0·0031	20
Lower stoss II a	4·94	0·0037	5	5·61	0·0053	20	4·68	0·0037	5
Lower stoss II b		0·0098	5		0·0074	5		0·0058	15
u_{12} (m s^{-1})	**10·02**			**11·81**			**9·57**		
Duration (min)	**16**			**10**			**20**		

The dune was divided into six flow regions (Figure 2); each was characterized by windspeed measurements from a vertical sampling profile and flux measurements from a staggered array of seven passive, wedge-shaped sediment traps (Nickling and McKenna Neuman, 1997). To minimize flow interference, traps were alternately spaced 2 m to either side of a centreline located 5 m east of the instrument transect. An entrance lip attached to the base of the sampling orifice helped reduce scour and assist sediment entry into the trap.

Wind velocity profile data measured at the crest were derived from four log-spaced instruments at 0·3, 0·7, 1·64 and 3·8 m. The surface anemometer recorded $u_{0\cdot3}$ at *c.* 1·2 m upwind of the crest and was coordinated with a nearby sediment trap located the same distance from the crest. Instruments were established most intensively within the lee separation zone. The lee slope region had four more closely spaced instruments located approximately two-thirds down the lee slope and approximately 2·5 m downwind of the crest. A surface anemometer recorded $u_{0\cdot3}$ along the lee slope and a sediment trap was located to the east at the same relative position. The upper three anemometers were aligned horizontally with the lower three positions of the crest profile. The interdune and stoss base profiles were instrumented as depicted with a vertical spacing of approximately 0·5 m between instruments. The lower stoss I profile was spaced with 0·6 m between instruments. Flux traps for interdune, stoss base and lower stoss I regions were located near the surface anemometers. In total, three traps were located within the separation zone including the stoss base trap located near reattachment. The point of flow reattachment (between the interdune and stoss base sampling profiles) was estimated visually by divergent surface ripple patterns and smoke tracers in the field. The lower stoss II profile consisted of four log-spaced instruments at 0·3, 0·6, 1·2 and 2·5 m with the upper anemometer at the same elevation as the third instrument on the crest profile. Two flux traps were located in the lower stoss II region, one in line with the surface anemometer (trap a) and the other 2 m downwind (trap b).

Windspeed and sediment transport data presented here are for three flux runs averaging 15 min in duration (Table I). Windspeeds were recorded as 1 min averages. An outer windspeed (u_{12}) was measured at a relative elevation of 12·4 m (*c.* 10h) above the interdune corridor atop an observation tower located approximately 9 m east of the sampling array. This outer windspeed was used to normalize all velocity data and ranged from 9·6 to 11·8 m s^{-1} (10·5 m s^{-1} average) during the period of study. Windspeeds for all runs were well above transport threshold (*c.* 6 m s^{-1}) at the crest and throughout most of the array. Intermittent and multidirectional transport was observed within the separation zone.

Prior to each flux run, trap orifices were plugged with a foam bung and aligned in the direction of transport by visual observation of local ripple crests and surface transport streamers. The collection period ended when the crest trap had collected 300–500 g of sediment (typically 10–20 min). Sample bags were then removed from the traps, weighed, and saved for grain size analysis. Samples greater than 100 g were split mechanically to obtain a representative sample of 50–100 g and were sieved in $\frac{1}{4}$ ϕ intervals from 1 ϕ to 4 ϕ in the laboratory. Samples of less than 100 g were sieved entirely. Grain size and sorting characteristics were calculated using the method of moments.

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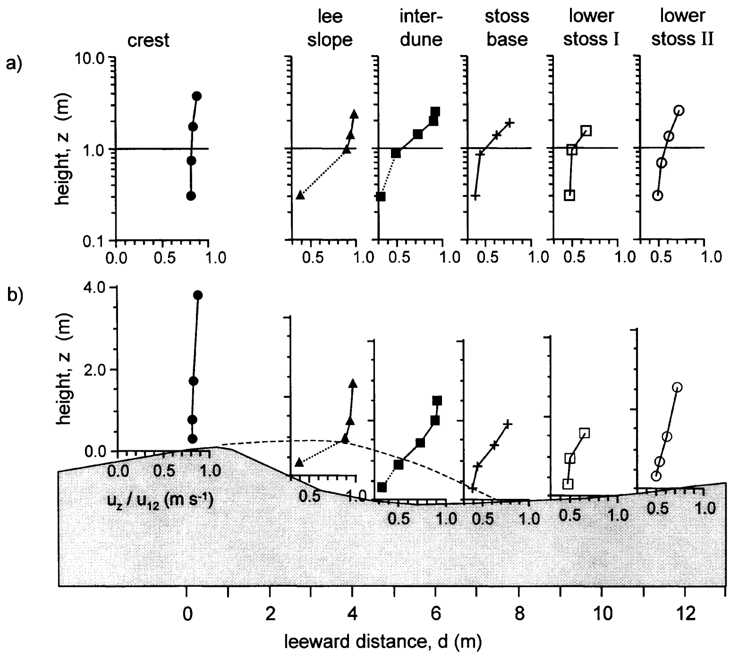

Figure 3. Time-averaged, normalized windspeed profiles derived from averaged data for all flux runs. Profiles for each flow region are plotted log-normally (a) to reveal deviations from the log-law, and in profile over the dune surface (b) to show windspeed variations at actual sampling heights. The dashed line extending from the crest delineates the extrapolated boundary of the separation cell. The dotted portions of the lee slope and interdune profiles indicate a flow direction that is strongly oblique to the incident direction at the crest (i.e. deflected interdune flow)

Variability in the magnitude and direction of lee-side sediment transport is characterized by flux vectors and discussed in comparison to transverse crest inputs. Given the limitations and uncertainties of estimating flux from a profile-derived shear velocity (u_*) over dunes (e.g. Wiggs, 1993; Wiggs *et al.*, 1996; Frank and Kocurek, 1996b; Lancaster *et al.*, 1996) measured sediment flux is related to a near-surface velocity at 0·3 m (e.g. McKenna Neuman *et al.*, 1997). Although recognized as relevant transport components, slip face avalanching and suspended fallout contributions are not considered in this study.

RESULTS

Lee-side velocity profiles

Variability in two-dimensional lee-side windspeeds for all three runs are characterized by normalized, time-averaged velocity profiles (Figure 3). The profiles represent the total average windspeeds for the measurement period. Profiles for each flow region are plotted log-normally (Figure 3a) to reveal deviations from the log-law, and in profile over the dune surface (Figure 3b) to show windspeed variations at actual sampling heights. Profiles are plotted at their relative locations over the dune surface (i.e. the $u_{0\cdot3}$ value for each profile in Figure 3b is located at the near-surface anemometer location). The extrapolated boundary of the separation cell is shown by the dashed line extending from the crest. The dotted portions of the lee slope and interdune profiles indicate a flow direction that is strongly oblique to the incident direction at the crest (i.e. deflected interdune flow).

The crest profile displays very little gradient below 2 m but steepens above this height indicating the influence of higher speed outer flow. Windspeeds in the lower portion of the crest profile are high and near-surface values average 0·82 of the outer flow (*c.* 8·4 m s^{-1}). Assuming that the windspeed at the base of the stoss slope (upwind) of the study dune may be of a similar magnitude to that measured in the lee, a speed-up

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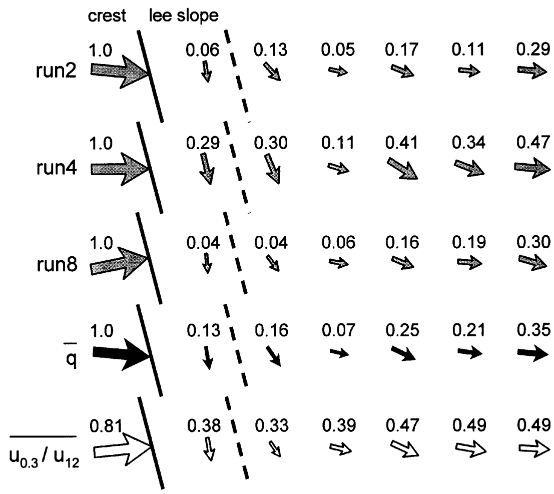

Figure 4. Lee-side sediment flux vectors for runs 2, 4 and 8. Flux values at each trap location are represented by proportionately sized symbols and were normalized by crest amounts. Total average flux values at each location are indicated by the black vector symbols. Average normalized near-surface windspeeds and directions for the total measurement period are shown by the white symbols at the bottom of the figure

ratio (Mason and Sykes, 1979) of 2·1 was estimated using average crest and stoss base windspeed values ($u_{0\cdot3\ \mathrm{stoss\ base}}/u_{0\cdot3\ \mathrm{crest}}$).

The lee slope profile is kinked with a steep gradient below the crest and a gradual, yet increased slope above the separation cell. Dimensionless speed on the lee slope averages 0·38 (*c.* 4 m s^{-1}) and increases rapidly to 0·89 (*c.* 9·3 m s^{-1}) just above crest height. The lower portion of the interdune profile exhibits a distinctly decreased gradient from that of the lee slope profile and has the lowest surface windspeed (0·33 or *c.* 3·5 m s^{-1}). The upper portion (> 1 m) has a clearly increased gradient although windspeeds are slower than those of the upper lee profile. The lower portions of the stoss base, lower stoss I and lower stoss II profiles show a gradual increase in gradient while upper portions show no visible change in slope. Relative velocities increase between these profiles up the stoss. The lower stoss II profile is more uniform in shape although an increased gradient remains evident in the upper portion.

Lee-side sediment flux vectors

Figure 4 shows vectors of flux magnitude and direction for three crest-transverse runs. Average flux and dimensionless near-surface windspeed vectors for the entire measurement period are shown as well. Flux values are dimensionless and were normalized by crest amounts. Vector angles represent trap alignments at each location although multidirectional and reversed flows were observed within the separation cell. Because trap sampling efficiency is reduced when flows are oblique to the trap inlet (Nickling and McKenna Neuman, 1997), measured flux amounts are relative approximations in the direction of trap alignment. This indicates a need for a rotating trap design that can sample in multidirectional flows.

Transport along the lee slope and within the interdune corridor ranges from 4 to 30 per cent and averages 13–16 per cent that of crest inputs. In addition, the direction of transport within the separation zone is acutely oblique (almost perpendicular) to the incident direction. Distinctly low sediment flux was measured at the stoss base location (fourth trap). In general, lee-side flux follows the increasing trend of near-surface windspeed beyond this point and transport direction progresses from laterally deflected to crest-transverse.

Relations between flux and windspeed

In light of the limitations and problems associated with using a profile-derived shear velocity (u_*) to estimate sediment transport over dunes, measured flux data were plotted against $u_{0\cdot3}$ (Figure 5). Although the

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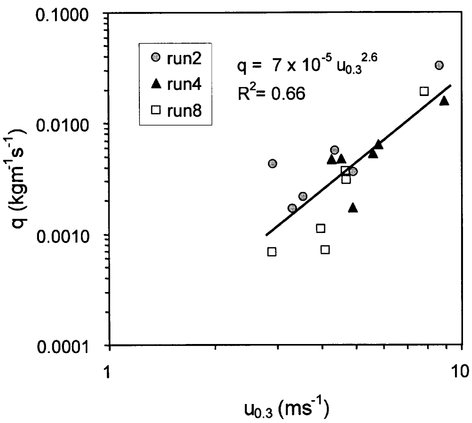

Figure 5. Relation between measured sediment flux (q) and windspeed ($u_{0{\cdot}3}$)

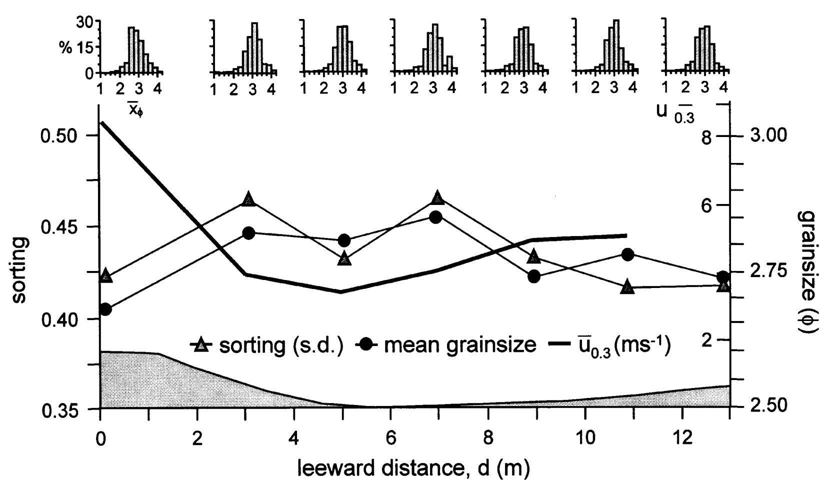

Figure 6. Variation in grain size and sorting characteristics of transported sediment in the lee

data are scattered, a positive relation exists between q and $u_{0{\cdot}3}$ in the lee. The power function regression $q \propto u_{0{\cdot}3}{}^{n}$, where $n = 2{\cdot}6$, describes the data set moderately well ($R^2 = 0{\cdot}66$). A threshold for lee transport of approximately 3 m s^{-1} is also evident.

Lee-side grain size and sorting characteristics

The variability in mean grain size, sorting and surface windspeed with distance from the crest (average values for all runs) is shown in Figure 6. Grain size distributions and average moment statistics for each trap location are shown in Figure 7. Sediment transported at the crest has the largest mean grain size (2·66ϕ), is well sorted (0·42) and is positively (fine) skewed (0·29). Within the separation zone (lee slope, interdune and stoss base locations), mean grain size decreases to *c.* 2·8ϕ and sediment becomes less well sorted as windspeed decreases rapidly. As windspeed increases upslope beyond reattachment, both mean grain size and sorting increase accordingly.

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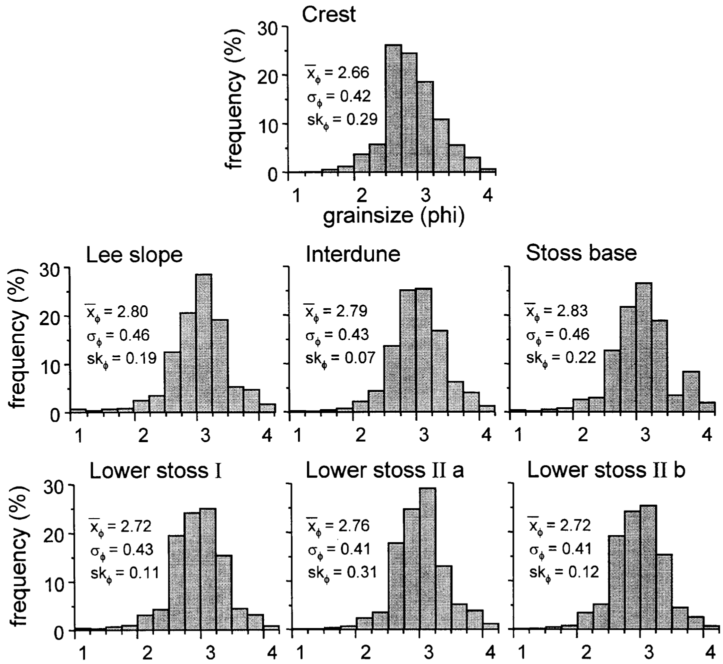

Figure 7. Grain size distributions at trap locations

DISCUSSION

Lee-side windspeed distribution

On the stoss slope of a dune, airflow is forced to compress and accelerate as it approaches the crest of a dune. This topographically induced speed-up effect has been documented extensively for flow over dunes (e.g. Howard *et al.*, 1978; Jensen and Zeman, 1985; Lancaster, 1985; Tsoar, 1985; Mulligan, 1988; Weng *et al.*, 1991; Burkinshaw and Rust, 1993; Frank and Kocurek, 1996b; Lancaster *et al.*, 1996; McKenna Neuman *et al.*, 1997). This speed-up effect occurs within a relatively thin inner layer (Taylor and Gent, 1974; Jackson and Hunt, 1975; Mason and Sykes, 1979) and has been estimated to be on the order of 0·01 m over larger reversing dunes in the same dunefield (McKenna Neuman *et al.*, 1997). The estimated speed-up ratio of 2·1 for this dune is comparable to the documented range of 1·1 to 2·0 for small to moderate sized dunes (e.g. Howard *et al.*, 1978; Lancaster, 1985; Tsoar, 1985; Mulligan, 1988; Lancaster *et al.*, 1996). There is no evidence though of acceleration, or bulging, in the lower crest profile, perhaps because the inner layer is very thin over these relatively small dunes. Hence, it is likely that anemometers at 0·3 m do not measure windspeed within the inner layer.

The kinked lee slope profile shown in Figure 3b reflects the influence of flow sheltering below the crest and acceleration of overshot flow above the crest. The upper boundary of the separation zone is just below the height of the second anemometer on the lee slope profile (where windspeed is approximately the same as at the crest). Assuming that windspeed will decrease along the line of separation below the crest, the boundary of the separation cell can be extrapolated to the point of reattachment near the base of the stoss base profile.

On average, near-surface windspeed ($u_{0\cdot 3}$) on the lee slope is approximately half (48 per cent) that at the crest. Within the lee slope flow region, windspeed decreases by 57 per cent from the boundary of the separation cell (i.e. from the second instrument location aligned horizontally with the crest surface anemometer) to 0·3 m above the lee slope surface. At this point along the separation zone boundary (approximately two dune heights downwind), windspeed increases by almost 10 per cent from that prior to

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separation at the crest. This indicates a region of high fluid shear within the separation zone. This may also be related to multidirectional and/or reversed secondary flow within the separation cell, although this remains to be explored.

Above the separation cell, profiles show a drastic increase in gradient (acceleration) although windspeeds are slower over the interdune. This behaviour corresponds with upper wake response as documented by Frank and Kocurek (1996a). The decrease in gradient in the lower portions of the lee slope and interdune profiles reflects flow expansion and deceleration within the separation zone. In the stoss base region, lower profile gradient continues to decrease as surface windspeed increases past the point of reattachment. Past this point, lower profiles accelerate and overall shape becomes progressively more uniform as the total velocity gradient is decreased. This is consistent with lower wake response past reattachment (Frank and Kocurek, 1996a). Although the lower stoss II profile is less kinked (Figure 3a), equilibrium between upper and lower wake regions is not observed by eight dune heights downwind (or 9·6 m in this case) as suggested by Frank and Kocurek (1996a). This suggests that wake recovery and inner boundary layer development may not occur completely over closely spaced dunes. The implication of this is that inner boundary layer development, and hence sediment transport, may be less than that encountered over more isolated dunes of similar size and shape. With these exceptions, profile behaviour in the lee is consistent with Frank and Kocurek's (1996a) model.

Spatial variability in lee-side sediment transport

As flow separates from the crest it expands, decelerates and loses momentum required for maintaining sediment in transport. Although a few grains may travel beyond the lee slope (Howard *et al.*, 1978), most sediment travels only as far as the characteristic saltation length and is deposited as fallout on the lee slope. Sediment transport measured on both the lee slope and interdune surfaces averages approximately 15 per cent of crest amounts. This suggests that a significant portion (*c*. 70–95 per cent) of sediment transported over the crest may move as fallout.

A distinctly low flux is noted near reattachment at the stoss base trap location. At this point flow begins to change towards a more transverse direction and may be in the early stages of inner boundary layer development, although this speculation is not confirmed in the windspeed profiles. It is also possible that observed multidirectional transport and downward motions of reattaching flow might have reduced trap sampling efficiency at this location. In general, there is an order of magnitude difference between flux at the crest and that measured in the separation zone.

Given the shallow depth of the inner layer, it is extremely difficult to estimate surface shear stress over dunes with much accuracy using the traditional u_* approach, especially with conventional three-cup anemometers. It follows that transport rates estimated from windspeed profiles measured above a few centimetres will be an underestimate (Frank, 1994; Frank and Kocurek, 1996b; McKenna Neuman *et al.*, 1997). Another approach is to compare directly measured transport with a near-surface windspeed. On the stoss slope of a larger reversing dune in the same dunefield, McKenna Neuman *et al.* (1997) documented a value of $n = 5{\cdot}6$ for the exponent of the relationship $q \propto u_{0{\cdot}3}{}^{n}$. Although there is no physical basis for this relationship, it serves as an empirical guideline for comparison. For the dataset presented here, flux is approximately proportional to the cube of the near-surface windspeed ($q \propto u_{0{\cdot}3}{}^{2{\cdot}6}$). The difference between these exponents may be related to the influence of secondary flow on measured flux within the separation cell. For instance, a threshold of $u_{0{\cdot}3} \approx 3$ m s^{-1} (Figure 5) is evident for transport in the separation zone, which is much less than the actual saltation threshold for this sand (*c*. 5–6 m s^{-1}). This may be explained in part by reduced threshold velocities on sloping surfaces (e.g. Howard *et al.*, 1978), as well as the contribution of fallout sediments captured by the lee traps. As a result, flux quantities measured in the immediate lee are associated with lower average windspeeds (3–4 m s^{-1}). The influence of these points would reduce the exponent of the relationship.

Transport direction in the separation zone is acutely oblique to the incident (crest) direction due to secondary flow deflection in the lee. This indicates that an appreciable amount of sediment moves laterally along the lee slope and interdune corridor under approximately crest-transverse flows. Beyond the interdune, transport direction progresses from along-dune to crest-transverse. These patterns are consistent with those

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documented for longitudinal dunes (e.g. Tsoar, 1978, 1982, 1983; Tsoar and Yaalon, 1983; Tsoar *et al.*, 1985; Livingstone, 1986).

Variability in grain size and sorting characteristics of transported sediment

In general, transported sediment throughout the study area is fine, well sorted and positively (fine) skewed. Crest sediment has the largest mean grain size reflecting the ability of accelerated crest flows to transport larger sediments. Within the separation zone (lee slope, interdune and stoss base locations), mean grain size decreases to *c.* $2{\cdot}8\phi$ and sediment becomes less well sorted. As windspeed decreases rapidly in this region, larger sediments cannot be transported, allowing only the finer particles to move in saltation along the surface. The decreased sorting trend may reflect a greater range of grain sizes overshot from the crest combined with coarse interdune sediment moving intermittently in gusty secondary flows. It is probable, given trap locations, that collected samples contain both coarser interdune and finer fallout sediments. Beyond reattachment, flow accelerates and both mean grain size and sorting increase accordingly.

Analysis of variance (one-way) was conducted on the means for grain size, sorting and skewness. Results indicate that there is no significant difference in mean grain size over the dune, although in general particles are finer in the lee. There is a significant difference in sorting and skewness within the lee, however, at the $\alpha = 0{\cdot}05$ confidence interval. Again, this may be related to the range of grain sizes collected in the lee traps from both fine fallout and coarse interdune sediment. This would reduce sorting and skew the distribution positively with the tail of coarser sediment (as in Figure 7) for the lee-side trap samples. It is important to note though that at the 96 per cent confidence interval ($\alpha = 0{\cdot}04$), there is no significant difference for both sorting and skewness. This stresses the need for further research into the effects of secondary flow on sediment size and sorting characteristics in the lee.

CONCLUSIONS

Several important conclusions are drawn from this study regarding secondary flow and sediment transport properties in the lee of transverse dunes. First, measured near-surface windspeeds indicate a sheltering effect on the lee slope of approximately half (48 per cent) the speed at the crest during transporting flow conditions ($u_{0{\cdot}3\mathrm{crest}} \approx 8{\cdot}4$ m s^{-1}). Dimensionless speeds in this region range from 0·2 at the surface to 0·8 along the upper boundary of the separation cell.

Second, windspeed within the immediate lee decreased by 57 per cent from the boundary of the separation cell to near the surface of the lee slope. By two dune heights downwind, windspeed increased along the separation zone boundary by almost 10 per cent of that prior to separation at the crest. Thus, high fluid shear exists within the separation cell and may be related to multidirectional and potentially reversed secondary flow within the separation cell.

Third, although stoss profiles become more uniform in shape (i.e. less kinked) in a downwind direction, equilibrium between upper and lower wake regions is not observed by eight dune heights as suggested by Frank and Kocurek (1996a).

Fourth, sediment transport on both the lee slope and interdune surfaces averages approximately 15 per cent of crest amounts. This suggests that a significant portion (*c.* 70–95 per cent) of sediment transported over the crest may move as fallout. In addition, transport direction in the separation zone is acutely oblique to the incident direction due to secondary flow deflection. This indicates that an appreciable amount of sediment moves laterally along the lee slope and interdune corridor under crest-transverse flow conditions. Beyond the interdune, surface flow and transport direction progress from along-dune to crest-transverse, which is consistent with documented patterns over longitudinal dunes.

Fifth, for the data presented here, sediment flux is approximately proportional to the cube of the near-surface windspeed ($q \propto {u_{0{\cdot}3}}^{2{\cdot}6}$). The exponent for this relationship is lower than that documented by McKenna Neuman *et al.* (1997) for larger dunes in the same area due, in part, to lower transport thresholds within the separation zone. This suggests that rates of transport over smaller and more closely spaced dunes may be significantly lower than larger, more isolated dunes.

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Future research must focus on the influence of three-dimensional secondary flow patterns on sediment transport and relate these to dune morphology for a range of incident angles and windspeeds.

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